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CHAPTER 10

Effect of a Legume Cover Crop on Carbon Storage and Erosion in an Ultisol under Maize Cultivation in Southern Benin

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10.1 INTRODUCTION

Soil organic matter (SOM) management is recognized as a cornerstone for successful farming in most tropical areas, with or without the application of mineral fertilizers (Merckx et al., 2001). Several experiments have demonstrated the direct or indirect positive effects of SOM on chemical, physical and biological properties of soil related to plant response (Sanchez 1976; Pieri 1991). Moreover, SOM is an essential reservoir of carbon (C), and SOM management can have significant implications on the global C balance and thus on climate change (Craswell and Lefroy 2001). In many rural areas of the tropics, the environmental challenge consists of reducing deforestation, increasing organic matter storage in cultivated soils, and reducing soil erosion. Therefore, under the economical conditions prevailing in developing countries, maintaining soil fertility and meeting the environmental challenge require land-use practices that include high levels of organic inputs and soil organic C sequestration (Feller et al. 2001).

Natural fallowing has long been the main practice to maintain soil fertility in tropical areas. However, as its effects only become significant after a period of at least 5 years, natural fallowing is no longer possible in the context of increasing population. Such is precisely the case in southern Benin, where the population density is 300 to 400 inhabitants km^{-2} (Azontonde 1993). The benefits of legume-based cover crops in Africa (in regions with annual rainfall > 800 mm) as an alternative to natural fallow, to control weeds and soil erosion, and enrich soil organic matter and N are widely recognized (Voelkner 1979; Raunet et al. 1999; Carsky et al. 2001). In southwestern Nigeria, higher maize (*Zea mays*) yields were obtained in live mulch plots under *Centrosema pubescens* or *Psophocarpus palustris* than in conventionally tilled and no-till plots for four consecutive seasons (Akobundu 1980).

The effect of relay-cropping maize through *Mucuna pruriens* (var. *utilis*) was assessed in southern Benin from 1988 to 1999 in terms of plant productivity and soil fertility (Azontonde 1993; Azontonde et al. 1998). The relay-cropping system (M) was compared with traditional maize cropping system without any input (T), and with a maize cropping system with mineral fertilizers (NPK). This paper focuses on changes in soil C during the period of the experiment in relation to residue biomass C returned to the soil, runoff and soil erosion losses, and loss of C with erosion.

10.2 MATERIALS AND METHODS

10.2.1 Description of the Site and Treatments

The experiment was conducted from 1988 to 1999 at an experimental farm at Agonkanmey (6°24'N, 2°20' E), near Cotonou in southern Benin in an area of low plateaus. The climate is subhumid-tropical with two rainy seasons (March–July and September–November). Mean annual rainfall is 1200 mm and mean annual temperature is 27°C. The soils are classified as Typic Kandiustult (Soil Survey Staff 1994) or Dystric Nitisols (FAO-ISRIC-ISSS 1998), and have a sandy loam surface layer overlying a sandy clay loam layer at about 50 cm depth. Most of the land is cultivated to maize (*Zea mays*), beans (*Vigna* sp.), cassava (*Manihot esculenta*), or peanuts (*Arachis hypogea*), often associated with oil palm (*Elaeis guineensis*).

The study was conducted on three 30 × 8 m plots on a 4% slope. These demonstration plots were not replicated, as it is usually difficult in long-term experiments (Shang and Tiessen 2000), especially when these include runoff plots. Three cropping systems were compared: T (traditional), maize without any input; NPK, maize with mineral fertilizers (200 kg ha^{-1} of NPK 15-15-15, and 100 kg ha^{-1} of urea); M, relay-cropping of maize and a legume cover crop, *Mucuna pruriens* var. *utilis*, with no fertilizer. Maize (var. *DMR*) was cropped during the first rainy season with shallow hoe tillage by hand (hoeing depth was about 5 cm). In M plot, maize was sown through the mucuna mulch from the previous year. Mucuna was sown one month later, and once maize had been harvested, its growth as a relay-crop continued until the end of the second (short) rainy season. During this short rainy season, the T and NPK treatments were maintained as natural fallow. Additional information on the site and soil properties has been provided by Azontonde (1993) and Azontonde et al. (1998).

10.2.2 Soil and Plant Sampling

Undisturbed soil profile samples were collected: (1) in March, June, August, and October 1988 and 1995, at 18 locations per plot for 0 to 10, 10 to 20, and 20 to 40 cm depths, using 0.2-dm^3 soil cores, and (2) in November 1999 at three locations per plot for 0 to 10 and 10 to 20 cm depths in two replicates, and for 20 to 30, 30 to 40, and 50 to 60 cm depths in one replicate, using 0.5-dm^3 soil cores. Soil samples were also obtained with a knife for different depths along the profile walls. Soil bulk density (Db) was determined after oven-drying core samples, whereas the other samples were air-dried, sieved (2 mm) and ground (< 0.2 mm) for C and N analyses.

Aboveground biomass of maize and mucuna was determined every year from five replicates (1 × 1 m) at maize harvest (August) and at mucuna maximum growth (October), respectively. In 1995, following the same pattern, roots of maize and mucuna were collected for 0 to 10, 10 to 20, and 20 to 40 cm depths, and hand-sorted (Azontonde et al. 1998). Annual root biomass was calculated using the ratio of below- to aboveground biomass determined in 1995, and the annual aboveground biomass. Sampling of the aboveground biomass of weed was done in November 1999 at nine locations per plot, using a 0.25 × 0.25-m frame. Litter was simultaneously and similarly sampled. Root sampling was also carried out in November 1999 on six 0.25 × 0.25 × 0.30-m monoliths per plot: monoliths were cut into three layers (corresponding to 0–10, 10–20, and 20–30 cm depths), and visible roots were hand sorted. With respect to the vegetation cover, we assumed that roots and litter sampled in T and NPK originated from weeds, whereas those sampled in M originated from mucuna. All plant samples were dried at 70°C, weighed for biomass measurement, and finely ground for C determination.

10.2.3 Carbon and Nitrogen Determination, and Other Analyses

Total C content (Ct) of soil samples collected in 1988 and 1995 was determined by the Walkley and Black method (WB), and total N content (Nt) by the Kjehldahl method. Both Ct and Nt of soil samples collected in 1999 were determined by the dry combustion method (DC) using an Elemental Analyzer (Carlo Erba NA 1500). The Ct was analyzed on 60 samples using both WB and DC methods, leading to a relationship ($r = 0.971$) that was used to convert WB data into DC data. All Ct data are thereafter expressed on a DC basis. The C content of plant samples was determined by dry combustion using an Elemental Analyzer (CHN LECO 600).

Particle-size analysis was performed by the pipette method after removal of organic matter with H_2O_2 and dispersion by Na-hexametaphosphate. Soil pH in water was determined using a 1:2.5 volumetric soil:solution ratio.

10.2.4 Determinations of Runoff, Soil Losses, and Eroded Carbon

Each plot was surrounded by half-buried metal sheets and fitted out with a collector draining runoff and sediments toward two covered tanks set up in series. When the first tank was full, additional flow moved through a multi-divisor tank into the second tank, both with a capacity of 3-m^3. Runoff and soil loss data were collected from 1993 to 1997.

Runoff amount (m^3) was assessed on every plot after each rainfall event or sequence of events, by measuring the volume of water in each tank and multiplying it by a coefficient depending on divisors. This runoff amount was converted to depth on the basis of the plot area. Annual runoff rate (mm mm^{-1}) was defined as the ratio of annual runoff depth to annual rainfall, and mean annual runoff rate as the ratio of runoff depth to rainfall over five years.

The amount of dry coarse sediments (Mg) was deduced by weighing wet coarse sediments collected in the first tank, and oven-drying the aliquots. The quantity of suspended sediments (Mg) was assessed by flocculation and oven drying of aliquots collected from each tank. Annual soil losses (Mg ha^{-1} yr^{-1}) were computed as the sum of dry-coarse and -suspended sediments over one year, and averaged over five years to calculate mean annual soil losses.

Annual eroded C (Mg C ha^{-1} yr^{-1}) was calculated as the product of annual soil losses by C content of sediments. Sediment C content was not measured, but was estimated as the product of soil Ct (at 0–10 cm depth, for the year under consideration) by an enrichment ratio (Starr et al. 2000). Soil Ct for the year under consideration was interpolated from soil Ct measurements carried out in 1988, 1995, and 1999. The enrichment ratio, defined as the ratio of Ct in sediments to that in the soil (0–10 cm depth), was estimated from the data in the literature: on light-textured Ultisols and Oxisols under maize cultivation (with mineral fertilizers) in southern and northern Ivory Coast, with 2100- and 1350-mm annual rainfall, respectively, C enrichment ratios measured in runoff plots by Roose (1980a, 1980b) were 1.9 (7% slope) and 1.4 (3% slope), respectively. Thus, C enrichment ratio of 1.6 was assumed for maize plots (T and NPK). In the absence of literature data regarding cover crops, C enrichment ratio under maize-mucuna (M) was found similar to those measured in runoff plots having comparable soil cover conditions: for two light-textured Oxisols under bush savannas in northern Ivory Coast, with 1200- and 1350-mm annual rainfall, respectively, C enrichment ratio measured by Roose and Bertrand (1972) and Roose (1980b) was 2.6 (4% slope) and 3.4 (3% slope), respectively; and for a sandy Ultisol under banana plantation in southern Ivory Coast (14% slope, 1800-mm annual rainfall), C enrichment ratio was 3 (Roose and Godefroy, 1977). Averaging these data, C enrichment ratio of 3 was assumed for maize-mucuna (M) rotation. Dissolved C in runoff was neither measured nor taken into consideration.

10.2.5 Statistical Analyses

Differences in mean Ct and Ct stocks were tested by a Student unpaired *t*-test. Differences in mean annual runoff rates, soil losses, and eroded C were tested by a paired *t*-test. In both cases, no assumptions were made on normality and variance equality (Dagnélie 1975).

10.3 RESULTS

10.3.1 General Properties of Soils (Table 10.1)

The clay (< 2 µm) content of the soil ranged between 110 and 150 g kg^{-1} for 0 to 10 cm depth in 1988, and it increased between 1988 and 1999 in T (50%) but not in NPK and M treatments (increase < 15%). The clay content also increased with depth. Moreover, clay content in 1999 was higher at 0 to 10 cm in T than at 10 to 20 cm in NPK and M treatments. The sand (> 50 µm) content was between 600 and 800 g kg^{-1} to 20 cm depth, mainly in the form of coarse sand (> 200 µm) (data not shown). Soil pH was acidic (< 6) and decreased between 1988 and 1999, especially in T and NPK treatments (–0.5 over a decade).

10.3.2 Soil Carbon

Total soil carbon content Ct (g C kg^{-1} soil) was determined through 18- and 3-replicate sampling in March 1988 and November 1999, respectively (Table 10.1). The validity of the latter was assessed using 18-replicate sampling done in October 1995 as a reference: following Dagnélie (1975) and Shang and Tiessen (2000), at 95% confidence level, irrespective of the plot and the depth, three-replicate sampling in 1995 would have led to a less than 8% relative error in Ct estimation. Thus, Ct determined in 1999 by three-replicate sampling was representative of the mean value of the plot. Similarly, Ct stock (Mg C ha^{-1}) estimated in November 1999 was representative of the large area.

Table 10.1 Soil Clay Content, pH in Water, Total Carbon Content Ct, C:N Ratio, and Total Carbon Stock in 1988 and 1999 (mean ± standard deviation when available)

	Depth (cm)	T		NPK		M	
		1988	1999	1988	1999	1988	1999
Clay (g kg^{-1})	0–10	147 ± 1	216	111 ± 6	128	127 ± 6	136
	10–20	nd	339	nd	198	nd	179
pH	0–10	5.6 ± 0.1	5.1	5.6 ± 0.1	5.2	5.2 ± 0.1	5.0
	10–20	5.4 ± 0.2	4.7	5.4 ± 0.2	5.0	5.1 ± 0.2	5.0
Ct (g kg^{-1})	0–10	5.5 ± 0.2	5.3 ± 0.1	5.4 ± 0.1	6.7 ± 1.8	5.2 ± 0.1	11.5 ± 2.0
	10–20	4.6 ± 0.3	4.0 ± 0.7	4.8 ± 0.4	3.8 ± 1.2	4.8 ± 0.4	7.3 ± 0.9
	20–30[a]	4.1 ± 0.2	3.5 ± 0.5	4.0 ± 0.4	3.6 ± 1.1	4.6 ± 0.3	4.4 ± 0.1
	30–40[a]		3.2 ± 0.1		4.1 ± 0.7		4.2 ± 0.2
	50–60	nd	2.4 ± 0.1	nd	3.5 ± 1.8	nd	3.3 ± 0.5
C:N	0–10	10.2 ± 1.0	12.2 ± 0.4	10.8 ± 0.5	11.3 ± 0.1	11.5 ± 0.5	11.9 ± 0.8
	10–20	10.9 ± 1.4	10.1 ± 0.6	10.7 ± 1.8	9.9 ± 0.7	12.0 ± 1.8	11.6 ± 0.8
	20–30[a]	11.4 ± 1.2	8.7 ± 0.5	10.6 ± 1.9	9.3 ± 1.0	12.8 ± 1.7	10.0 ± 1.2
	30–40[a]		8.2 ± 0.8		8.8 ± 1.4		8.9 ± 1.3
	50–60	nd	7.0 ± 0.4	nd	8.8 ± 3.2	nd	8.1 ± 1.4
Ct stock (Mg C ha^{-1})	0–10	7.7 ± 0.7	8.4 ± 0.3	7.3 ± 0.5	10.6 ± 3.4	6.8 ± 0.3	17.4 ± 3.3
	0–20	13.6 ± 0.9	14.5 ± 0.4	14.6 ± 1.0	17.0 ± 3.9	13.8 ± 0.8	28.7 ± 3.9
	0–40	25.9 ± 1.5	24.2 ± 0.5	27.0 ± 1.8	28.8 ± 5.7	27.7 ± 1.7	41.4 ± 4.9
	0–60	nd	32.0 ± 0.3	nd	39.7 ± 3.6	nd	51.7 ± 4.1

Note: nd: not determined.

[a] 20–40 cm in 1988.

Differences in Ct between plots were negligible (< 2% at 0–20 cm) in March 1988. Between March 1988 and November 1999, Ct increased considerably at 0 to 20 cm depth in M (90%, $p < 0.01$) but changed slightly in T (–8%) and NPK (3%), and for 20 to 40 cm depth (changes < 20%). In November 1999, and as a consequence, Ct at 0 to 20 cm depth was much greater in M than in T (100%, $p < 0.01$) and NPK (80%, $p < 0.05$) treatments. Differences between plots were rather small below this depth, as were differences between NPK and T (< 30% in general) treatments.

Changes in Ct stock (Mg C ha^{-1}) for 0 to 40 cm depth were similar showing small initial differences between plots (< 7%); between March 1988 and November 1999, slight changes in T and NPK (< 15%) treatments but a considerable increase in M (50%, $p < 0.01$); higher final Ct stock in M than in T (70%, $p < 0.01$) and NPK (45%, $p < 0.05$) treatments. Stock of Ct for 0 to 40 cm depth finally attained the value of 24, 29, and 41 Mg C ha^{-1} in T, NPK, and M, respectively. Between 1988 and 1999, mean (± standard deviation) annual changes in Ct stock were 0.1 (±0.1), 0.2 (±0.4), and 1.4 (±0.4) Mg C ha^{-1} yr^{-1} in T, NPK, and M, respectively, for 0 to 20 cm depth; and –0.2 (±0.1), 0.2 (±0.5), and 1.3 (±0.5) Mg C ha^{-1} yr^{-1}, respectively, for 0 to 40 cm depth.

10.3.3 Residue Biomass

Average annual residue biomass (dry matter) returned to the soil in T, NPK, and M was 8, 13, and 19.9 Mg ha^{-1} yr^{-1}, with 35, 72, and 82% of aboveground biomass, respectively (Table 10.2). Mean annual residue C added was 3.5, 6.4, and 10 Mg C ha^{-1} yr^{-1}, with 39, 74, and 84% as aboveground biomass, respectively (aboveground biomass had a slightly more C content than roots). Returned C mainly originated from weeds in T (55% as roots and 17% as aboveground biomass), which represented 44 and 92% of aboveground and belowground residue C, respectively. In contrast, returned C in NPK was mainly from maize (61% as aboveground biomass and 14% as roots). In M, maize and mucuna accounted for similar amounts of residue C, either as aboveground biomass (about 40% each) or roots (8% each). Moreover, maize residue biomass C was of the same order of magnitude in NPK and M (ca. 5 Mg C ha^{-1} yr^{-1}) treatments.

Table 10.2 Residue Biomass Returned to the Soil (mean ± standard deviation)

Origin	Residue Biomass (dry matter) (Mg ha^{-1} yr^{-1})			C Content of Residues (g C kg^{-1})			Residue Biomass C (Mg C ha^{-1} yr^{-1})			C:N of Residues		
	T	NPK	M	T	NPK	M	T	NPK	M	T	NPK	M
Maize												
Aboveground	1.44 ± 0.06	7.46 ± 0.19	8.05 ± 0.20	533 ± 26	524 ± 16	538 ± 10	0.77 ± 0.03	3.91 ± 0.12	4.33 ± 0.12	118	75	84
Roots	0.42 ± 0.01	1.76 ± 0.05	1.67 ± 0.07	474 ± 20	508 ± 20	456 ± 21	0.20 ± 0.01	0.89 ± 0.04	0.76 ± 0.03	121	78	91
Subtotal	1.86 ± 0.07	9.22 ± 0.19	9.72 ± 0.21	519 ± 33	521 ± 26	524 ± 23	0.97 ± 0.03	4.80 ± 0.12	5.10 ± 0.13	118	75	86
Mucuna												
Aboveground	0.00	0.00	8.34 ± 0.24	—	—	488 ± 25	0.00	0.00	4.07 ± 0.12	—	—	18
Roots	0.00	0.00	1.88 ± 0.06	—	—	455 ± 20	0.00	0.00	0.85 ± 0.03	—	—	22
Subtotal	0.00	0.00	10.22 ± 0.25	—	—	482 ± 32	0.00	0.00	4.93 ± 0.13	—	—	19
Weeds												
Aboveground	1.36 ± 0.39	1.89 ± 0.29	0.00	440 ± 12	430 ± 10	—	0.60 ± 0.18	0.82 ± 0.14	0.00	35	25	—
Roots[a]	4.77 ± 1.81	1.89 ± 0.92	0.00	400	400	—	1.91 ± 0.72	0.75 ± 0.37	0.00	nd	nd	—
Subtotal	6.13 ± 1.85	3.78 ± 0.96	0.00	409	415	—	2.51 ± 0.74	1.57 ± 0.40	0.00	nd	nd	—
Subtotal												
Aboveground	2.80 ± 0.40	9.35 ± 0.34	16.39 ± 0.32	488 ± 29	505 ± 19	513 ± 27	1.37 ± 0.18	4.73 ± 0.18	8.41 ± 0.17	78	65	51
Roots	5.19 ± 1.81	3.65 ± 0.92	3.55 ± 0.09	406	452	455 ± 29	2.11 ± 0.72	1.64 ± 0.37	1.61 ± 0.04	nd	nd	55
Total	7.99 ± 1.85	13.00 ± 0.98	19.94 ± 0.33	435	490	503 ± 40	3.48 ± 0.74	6.37 ± 0.41	10.02 ± 0.18	nd	nd	52

Note: nd: not determined.

[a] 0–30 cm; data resulting from sampling carried out in November 1999, assuming that roots collected in T and NPK were weed roots only and had a C content of 400 g C kg^{-1}.

Table 10.3 Annual Runoff Rates, Soil Losses, and C Erosion

Year	Rainfall ($mm\ yr^{-1}$)	Runoff Rate ($mm\ mm^{-1}$) T	NPK	M	Soil Losses ($Mg\ ha^{-1}\ yr^{-1}$) T	NPK	M	C Erosion ($Mg\ C\ ha^{-1}\ yr^{-1}$) T	NPK	M
1993	1288	0.30	0.13	0.09	41.5	9.8	3.1	0.4	0.1	0.1
1994	1027	0.20	0.10	0.06	31.2	8.2	2.2	0.3	0.1	0.1
1995	1000	0.16	0.08	0.04	10.6	3.8	1.3	0.1	0.0	0.0
1996	1126	0.25	0.12	0.08	40.4	8.9	2.5	0.3	0.1	0.1
1997	1558	0.40	0.15	0.11	46.3	15.6	5.5	0.4	0.2	0.2
Mean	1200	0.28	0.12	0.08	34.0	9.3	2.9	0.3	0.1	0.1
SD[a]	230	0.09	0.03	0.03	14.2	4.2	1.6	0.1	0.0	0.1

[a] SD: standard deviation.

10.3.4 Runoff, Soil Losses, and Eroded Carbon

Annual rainfall ranged between 1000 and 1558 mm, and averaged 1200 mm between 1993 and 1997 (Table 10.3). Mean annual runoff rate in T, NPK, and M treatments was 0.28, 0.12, and 0.08 $mm\ mm^{-1}$, and mean annual soil losses was 34.0, 9.3, and 2.9 $Mg\ ha^{-1}\ yr^{-1}$, respectively. Using C enrichment ratios of sediments determined in similar soil and climate conditions (Roose, 1980a, 1980b), mean eroded C was estimated at 0.3, 0.1, and 0.1 $Mg\ C\ ha^{-1}\ yr^{-1}$ in T, NPK, and M treatments, respectively. In plots vulnerable to erosion, eroded C was thus of the same order of magnitude as changes in Ct stock for 0 to 40 cm depth: –0.3 vs. –0.2 $Mg\ C\ ha^{-1}\ yr^{-1}$ in T, and –0.1 vs. 0.2 $Mg\ C\ ha^{-1}\ yr^{-1}$ in NPK. In contrast, eroded C in M was negligible compared with changes in Ct stock: –0.1 vs. 1.3 $Mg\ C\ ha^{-1}\ yr^{-1}$. Moreover, mean annual runoff rate and soil losses were significantly more in T than in NPK and more in NPK than in M; and eroded C was more in T than in NPK and M ($p < 0.01$) treatments. Additionally, mean annual runoff rate, soil losses, and eroded C increased with the increase in annual rainfall.

10.4 DISCUSSION

10.4.1 Changes in Soil Carbon

At the end of our experiment, Ct stock for 0 to 40 cm depth was 24 $Mg\ C\ ha^{-1}$ under unfertilized maize, 29 $Mg\ C\ ha^{-1}$ under fertilized maize, and 41 $Mg\ C\ ha^{-1}$ under maize-mucuna rotation. Elsewhere in southern Benin and in similar soil conditions, Djegui et al. (1992) reported Ct stocks for 0 to 35 cm depth at 27 $Mg\ C\ ha^{-1}$ under oil palm plantation, 30 $Mg\ C\ ha^{-1}$ under food crops (with fallow), and 48 $Mg\ C\ ha^{-1}$ under forest.

The data on Ct stock presented herein are consistent with other published data (Table 10.4). For an Alfisol in southwestern Nigeria, rates of 0.2 $Mg\ C\ ha^{-1}\ yr^{-1}$ were recorded for 0 to 10 cm depth for fertilized maize (Lal 2000), vs. 0.3 $Mg\ C\ ha^{-1}\ yr^{-1}$ for NPK; in Brazilian Ultisols and Oxisols, rates of around 1 $Mg\ C\ ha^{-1}\ yr^{-1}$ were measured for 0 to 20 cm depth under long-term no-till cropping systems (Bayer et al. 2001; Sá et al. 2001), vs. 1.4 $Mg\ C\ ha^{-1}$ in M; in a Nigerian Alfisol, rates beyond 2 $Mg\ C\ ha^{-1}\ yr^{-1}$ have even been measured for 0 to 20 cm depth under a 2-year *Pueraria* cover (Lal 1998). These data confirm that residue mulching increases Ct stock in tropical soils, especially in cropping systems including legume cover crops.

10.4.2 Residue Biomass

The high rates of Ct increase in M resulted first from high residue biomass returned to the soil, which averaged 20 $Mg\ ha^{-1}\ yr^{-1}$ (dry matter). The aboveground biomass of mucuna was 8 $Mg\ ha^{-1}$

Table 10.4 Compared Values of Annual Changes in Ct Stock under Various Tropical Cropping Systems Including Reduced or No Tillage

Country and Soil Type	Cropping System (and duration, in yr)	Change in Ct Stock (Mg C ha^{-1} yr^{-1})	Reference
	For 0–20 cm Depth		
Nigeria, Alfisol	*Pueraria sp.* (2)	+2.1	Lal (1998)
Benin, Ultisol	maize-mucuna (11)	+1.4	this chapter
Brazil, clayey Oxisol	cereals and soybean (10, 22)	+1.0	Sá et al. (2001)
Brazil, clay loam Ultisol	*Cajanus cajan*-maize (12)	+0.9[a]	Bayer et al. (2001)
Nigeria, Alfisol	*Stylosanthes sp.* (2)	+0.4	Lal (1998)
Benin, Ultisol	fertilized maize (11)	+0.2	this chapter
Nigeria, Alfisol	*Centrosema sp.* (2)	+0.1	Lal (1998)
Benin, Ultisol	nonfertilized maize (11)	+0.1	this chapter
	For 0–10 cm Depth		
Benin, Ultisol	maize-mucuna (11)	+1.0	this chapter
Nigeria, Alfisol	*Cajanus cajan*-maize (3)	+0.7	Lal (2000)
Honduras, various soils	mucuna-maize (1 to 15)	+0.5[b]	Triomphe (1996a)
Benin, Ultisol	fertilized maize (11)	+0.3	this chapter
Nigeria, Alfisol	fertilized maize (3)	+0.2	Lal (2000)
Benin, Ultisol	nonfertilized maize (11)	+0.1	this chapter

[a] For 0–17.5 cm depth.
[b] From +0.2 to +1.4 Mg C ha^{-1} yr^{-1}, depending on the site.

y^{-1}, within the range of published data: 6 to 7 Mg ha^{-1} yr^{-1} in 1-year mucuna fallows in Nigeria (Vanlauwe et al. 2000) and an average of 11 Mg ha^{-1} yr^{-1} in mucuna-maize systems in Honduras (> 2000-mm annual rainfall; Triomphe 1996b). The ratio of change in Ct stock to residue C measured in these plots also agreed with data in the literature: in a 12-year no-till maize-legume rotations on a sandy clay loam Ultisol in Brazil, Ct stock increase for 0 to 17.5 cm depth represented 11 to 15% of aboveground residue C (Bayer et al. 2001), vs. 15% in M (and 5% in NPK). In contrast, in long-term no-till cereal–legume rotations on clayey Oxisols also in Brazil, the increase in Ct stock for 0 to 40 cm depth represented 22 to 25% of total residue C (Sá et al. 2001), vs. 12% in M (and 3% in NPK). This difference confirms the role of clay content for C sequestration through the development of stable aggregates and hence organic matter protection (Feller and Beare 1997).

In plots that were left under natural fallow during the short rainy season, weeds represented an important proportion of residue biomass, i.e., 77% in T and 29% in NPK. Weeds represented about 50% of the aboveground residue biomass in T, as was also the case in nonfertilized maize plots studied in Nigeria (Kirchhof and Salako 2000). These data underline the need for systematic measurements of weed biomass when it represents a noticeable proportion of biomass returned to the soil. In our experiment, weeds were sampled on one day only, and it is likely that it led to some uncertainties. Weed biomass was negligible in M: proportions of aboveground residue biomass for maize, mucuna, and weeds were 49, 51, and 0%, respectively. Similarly, these proportions were 49, 42, and 9%, respectively, in 1–year maize-mucuna plots studied in Nigeria (Kirchhof and Salako 2000). Indeed, Carsky et al. (2001) reported that weed suppression was often cited as the reason for the adoption of mucuna fallow systems in Africa.

10.4.3 Nitrous Oxide Emissions

Use of nitrogenous fertilizers also impacts nitrous oxide (N_2O) emissions, which can be roughly estimated using Equation 10.1 (Bouwman 1996):

$$\text{N-N}_2\text{O emissions (kg ha}^{-1}\text{ yr}^{-1}) = 1 + [0.0125 \times \text{N-fertilizer (kg ha}^{-1}\text{ yr}^{-1})] \qquad (10.1)$$

In NPK, N fertilizer was used at the rate of 76 kg N ha^{-1} yr^{-1} (Azontonde et al. 1998). Following Equation 10.1, it resulted in 2-kg N-N_2O ha^{-1} yr^{-1} emissions. As the global warming potential of N_2O is about 300 times that of CO_2 (IPCC, 2001), these N_2O emissions were equivalent to more than 0.2-Mg C-CO_2 ha^{-1} yr^{-1} emissions, and thus offset Ct increase (0.2 Mg C ha^{-1} yr^{-1}).

In M, mucuna residues supplied the soil with more than 250 kg N ha^{-1} yr^{-1} (Azontonde et al. 1998). In this case, Equation 10.1 led to an overestimation of N_2O emissions, as it was established from a set of experiments excluding legume cover crops, which provide N that is less directly available than mineral fertilizers. However, it may give an order of magnitude: by following Equation 10.1, N supply by mucuna residues resulted in 4-kg N-N_2O ha^{-1} yr^{-1} emissions, equivalent to 0.5-Mg C-CO_2 ha^{-1} yr^{-1} emissions (vs. 1.3 Mg C ha^{-1} yr^{-1} as Ct increase). Though overestimated, these data indicate that from an environmental point of view, Ct increase in soils under legume cover crops could be partly offset by N_2O emissions.

10.4.4 Runoff, Soil Losses, and Eroded Carbon

As compared with T, mean annual runoff rate and soil losses were 57 and 73% less in NPK, respectively, and were 71 and 91% less in M, respectively. Protection of the soil surface by vegetation and residues dissipates kinetic energy of rainfall and has an important influence on the reduction of runoff and erosion (Wischmeier and Smith 1978). Thus, groundcover by mucuna mulch was probably the main reason for less runoff and soil losses in M than in T and NPK treatments. Similarly but to a lesser extent, it is likely that due to large biomass, fertilized maize provided a better groundcover than unfertilized maize. Additionally, residue return determines an increase in SOM that favors aggregate stability (Feller et al. 1996), thus preventing detachment of easily transportable particles, and thereby reducing surface clogging, runoff, and erosion (Le Bissonnais 1996) Therefore, higher Ct also resulted in less runoff and erosion in M than in NPK, and also less in NPK than in T treatment.

With respect to runoff plots from tropical areas cropped with maize (or sorghum), comparisons with published data show that annual runoff rate was high (> 0.25 mm mm^{-1}) in T and under humid conditions (2100-mm annual rainfall); soil losses were high (> 20 Mg ha^{-1} yr^{-1}) under humid or semiarid conditions (500-mm annual rainfall) and in nonfertilized plots (Table 10.5). In contrast, runoff rate was low (< 0.10 mm mm^{-1}) on steep slopes with clayey soils (Kenya) and under maize-mucuna (M); soil losses were low (< 5 Mg ha^{-1} yr^{-1}) in M treatment. Thus, runoff and erosion increased with increase in annual rainfall and/or with a decrease in soil surface cover (absence of mulch, nonfertilized plots, semiarid conditions), in accordance with usual observations (Wischmeier and Smith 1978; Roose 1996). Under nonfertilized maize in Kenya, low runoff rates (0.02 mm mm^{-1}) resulted in high soil losses (29 Mg ha^{-1} yr^{-1}); assuming that the clayey Alfisol in this study had a stable structure with a high infiltration rate, steep slopes (30%) probably determined the nonselective transport of aggregates in the absence of adequate groundcover.

Mean annual C erosion was estimated at 0.3, 0.1, and 0.1 Mg C ha^{-1} yr^{-1} in T, NPK, and M treatments, respectively. Though mean soil losses were three times more in NPK than in M, eroded C was similar in both treatments probably because of high C content in surface soil (which supplies sediments) and higher C enrichment ratio of sediments in M than in NPK treatments. Indeed, several experiments have indicated that C enrichment ratio increases with decrease in soil losses (Roose 1980a, 1980b). Thus, mucuna mulch was less effective in reducing the amount of C erosion than in reducing runoff and soil losses; but it was very effective in reducing the proportion of topsoil C that was eroded, which was much lesser in M than in NPK treatments. This underlines the interest of referring C erosion to topsoil C (enrichment ratio), and to temporal changes in topsoil C.

These data are consistent with those reported in the literature, which showed that C erosion significantly increased with increase in the product of soil losses and soil Ct stock ($r = 0.932$, $p < 0.01$; Figure 10.1, drawn up from Table 10.5). The data reported herein show that either soil Ct

Table 10.5 Compared Values of Annual Runoff Rate, Soil Losses, and C Erosion from Runoff Plots Cropped with Maize (or sorghum) in Tropical Areas

Country	Rainfall (mm yr^{-1})	Slope (%)	Soil Type	Ct Stock[a] (Mg C ha^{-1})	Runoff Rate (mm mm^{-1})	Soil Losses (Mg ha^{-1} yr^{-1})	C Erosion (Mg C ha^{-1} yr^{-1})	Reference
				Nonfertilized Maize				
Kenya	1000	30	Clayey Alfisol	80	0.02	29.0	2.4	Gachene et al. (1997)
Benin	1200	4	Sandy loam Ultisol	20	0.28	34.0	0.3	this chapter
				Fertilized Maize (or Sorghum)				
Ivory Coast	2100	7	Sandy loam Ultisol	34	0.27	89.4	1.8	Roose (1980a)
Kenya	1000	30	Clayey Alfisol	80	0.01	8.4	0.7	Gachene et al. (1997)
Burkina Faso	800	1	Sandy Alfisol	13	0.25	7.3	0.2	Roose (1978)
Zimbabwe	500	5	Sandy Alfisol	15?	0.17	20.6	0.2	Moyo (1998)
Ivory Coast	1350	3	Sandy (gravely) Oxisol	21	0.20	5.5	0.1	Roose (1980b)
Benin	1200	4	Sandy loam Ultisol	22	0.12	9.3	0.1	this chapter
				Maize-Mucuna				
Benin	1200	4	Sandy loam Ultisol	35	0.08	2.9	0.1	this chapter

[a] At 0–30 cm.

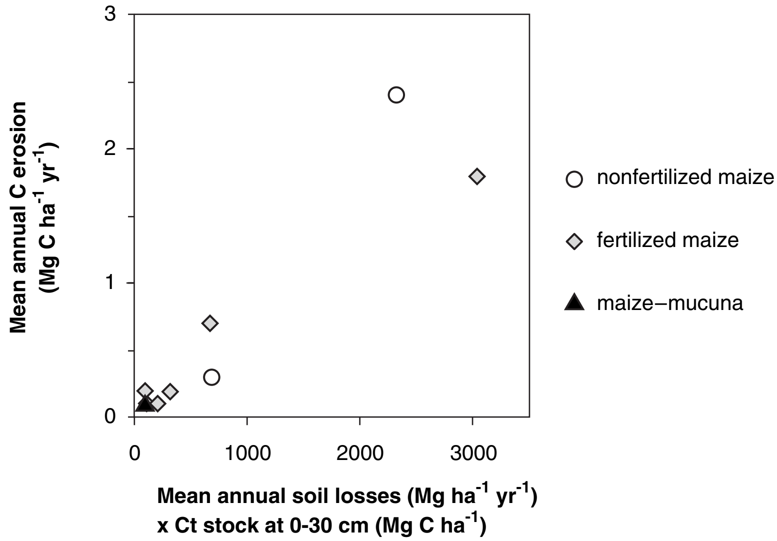

Figure 10.1 Relationship between mean annual C erosion (Mg C ha^{-1} yr^{-1}) and the product of mean annual soil losses (Mg ha^{-1} yr^{-1}) into Ct stock of bulk soil at 0–30 cm (Mg C ha^{-1}) (data from Table 10.5).

stock (T and NPK) or soil losses (M) were rather small, thus C erosion was much smaller than in studies from Kenya (high soil Ct stocks on steep slopes) and Ivory Coast (humid conditions), where it ranged from 0.7 to 2.4 Mg C ha^{-1} yr^{-1}.

10.5 CONCLUSION

For this sandy loam Ultisol, relay-cropping of maize and mucuna (M) was very effective in enhancing C sequestration: change in Ct stock for 0 to 40 cm depth was 1.3 Mg C ha^{-1} yr^{-1} over the 12-year period of the experiment, ranging among the highest rates recorded for the eco-region. This increase resulted first from the high amount of residue biomass provided by mucuna, which amounted to 10 Mg DM ha^{-1} yr^{-1} (83% aboveground). Mucuna residues, supplying the soil with N, also favored the production of maize biomass, and total mucuna plus maize residue biomass returned to the soil was about 20 Mg ha^{-1} yr^{-1}. These results indicate the usefulness of mucuna for SOM management. In contrast, nonfertilized (T) and fertilized continuous maize cultivation (NPK) resulted in –0.2- and 0.2-Mg C ha^{-1} yr^{-1} change in Ct stock for 0 to 40 cm depth, respectively. Total residue biomass was 8 and 13 Mg ha^{-1} yr^{-1}, including 77 and 29% by weeds, respectively. These contributions demonstrate the need for weed biomass sampling, especially when noticeable rainfall occurs beside the cropping season. Weed biomass was negligible in M, underlining the potential of mucuna for weed control.

Moreover, the thick mulch produced by mucuna decreased losses by runoff and erosion, which were 0.28, 0.12, and 0.08 mm mm^{-1}, and 34, 9, and 3 Mg ha^{-1} yr^{-1} in T, NPK, and M treatments, respectively. Eroded C was estimated at 0.3, 0.1, and 0.1 Mg C ha^{-1} yr^{-1} in T, NPK, and M, respectively. Thus, C erosion was of the same order of magnitude as changes in soil Ct stock in treatments vulnerable to erosion (T and NPK). In contrast, C erosion under maize-mucuna was negligible as compared to changes in soil Ct stock.

Through its benefits on SOM management, weed suppression, and erosion control, cropping systems including a legume cover may have an adverse impact from a global change standpoint. Indeed, rough estimates show that N_2O emissions resulting from N supply by mucuna may partly offset soil C storage in M treatment. In NPK, N_2O fluxes consecutive to mineral N supply could even offset soil C storage completely. In order to characterize these adverse effects and establish greenhouse gas balances precisely, there is an urgent need for accurate field measurements of N_2O fluxes, especially in cropping systems including legumes.

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